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INVESTIGATION OF THE INTERACTION OF A SPHERICAL SHOCK WAVE WITH BODIES

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INVESTIGATION OF THE INTERACTION OF A SPHERICAL SHOCK WAVE WITH BODIES

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ABSTRACT: This paper reviews the interaction of a spherical explosion wave featured by significant unsteadiness of the flow behind the shock wave. The pulse force (the integral of the force in terms of time) communicated by the explosion wave to a stationary cylindrical body was measured, and the formation of the picture of the flow near a blunt flying body was investigated.

Most of the results of the investigation of the interaction of shock /115* waves with bodies are obtained experimentally in shock tubes characterized by constant parameters for the flow behind the wave front, as is the case in [1, 2], for example. This paper reviews the interaction of a spherical explosion wave featured by a significant unsteadiness of the flow behind the shock wave. The pulse force (the integral of the force in terms of time) communicated by the explosion wave to a stationary cylindrical body was measured, and the formation of the picture of the flow near a blunt flying body was investigated.

1. Measurement of the force pulse. A chemical explosive charge was detonated during the experiments to form the spherical shock wave. The wave interacted with a cylinder of circular cross section freely suspended by thin wires in a direction perpendicular to the direction of propagation of the shock wave. Since cylinder mass remained constant throughout the experiment, and since the reactions of the suspension wires in the direction of motion can be ignored, the magnitude of the force pulse at each moment in time is proportional to body speed. Two methods were used to find instantaneous speeds. One used an electrical signal time integrator, with the signal supplied by a piezoelectric accelerometer installed on the body, and the other used the electromagnet method.

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* Numbers in the right margin indicate pagination in the foreign text.

A type IS-313 piezoelectric accelerometer, 16 x 16 x 19 mm^3, with a sensitivity of 0.5 millivolt $second^2$/meter, was installed in the center of the cylinder to obtain the measurements by the first of these methods. The signal from the accelerometer was transmitted over an antivibration cable to a preamplifier, then integrated with respect to time by an integration amplifier and recorded on a two-channel oscilloscope. The second channel of the oscilloscope was used to record the signal from the accelerometer for the excess static pressure behind the front of the explosion wave [3]. A piezoelectric synchronization pickup triggered the oscilloscope. /116

Prior to the installation of the accelerometer in the cylinder, the entire channel used to measure the speed was calibrated by a pneumatic device consisting of a high-pressure chamber, a section of cylindrical pipe, and a quick-acting electrically operated valve that prevented the air from entering the pipe from the chamber. A piston, and a bracket for securing the calibrated pickup, were installed in the pipe close to the valve. The piston moved with uniform acceleration when the valve was opened, and its speed at each moment in time was determined by the known values for initial air pressure in the chamber, area of the transverse section of the piston, and mass of piston and accelerometer.

The static pressure pickup was calibrated by a pneumatic pulser [4].

The installation of the accelerometer in the cylinder involved centering the accelerometer with set screws and filling the cylinder with Wood's metal with a melting point of 60°C. This method simplified installation and removal of the accelerometer, and increased the frequency of the accelerometer's natural oscillations with respect to the cylinder.

The cylinder itself, made of current-conducting material and set in a constant magnetic field with an intensity of approximately 150 oersteds, uniform in the direction in which the shock wave was moving, was the speed pickup when the electromagnet method was used. The field was created by an electromagnet with pole tips, the sections of which measured 10 x 200 mm^2, oriented with respect to the center of the explosion and fitted with deflectors. Control measurements in the working zone between the poles, made with static and full pressure pickups [3], revealed that the presence

of the electromagnet had practically no effect on the nature of the flow behind the front of the explosion wave. Two thin, rigid, electrodes, oriented in the direction cylinder movement, were fastened to the cylinder. The emf induced across the ends of the electrodes as the cylinder was moved by the explosion wave was recorded on a two-channel oscilloscope. A signal from the piezoelectric static pressure pickup was supplied to the second channel, as in the first method.

Calibration of the channel used to measure speed by the electromagnet method was by the pneumatic device described above. The piston of the calibrating device was rigidly connected to the cylinder under investigation and installed directly in the test zone.

The total error in measuring the force pulses by both methods described was not in excess of 10%, while the error in the static pressure measurement was 3%.

The accelerometer was used to measure the force pulse communicated by the explosion wave to cylinders with diameters D = 28 mm (210 mm long), and D = 50 mm (300 mm long). The electromagnet method was used to investigate the initial section of the pulse curve for cylinders with diameters D = 28 mm (210 mm long) and D = 10 mm (100 mm long).

All cylinders were tested at a fixed distance of 5.1 meters from the center of the explosion, with initial air pressure p_o = 1.0; 0.3 kg/cm^2. The relative static pressure drop at the explosion wave front was

$$\frac{\Delta p_1}{p_o} = \begin{cases} 0.25 \text{ to } 1.1 \text{ for } p_o = 1.0 \text{ kg/cm}^2 \\ 0.4 \text{ to } 1.1 \text{ for } p_o = 0.3 \text{ kg/cm}^2 \end{cases}$$

Typical oscillograms for a force pulse, I, in terms of time, T, obtained with the cylinder for various shock wave parameters, are shown in Figures 1 a, b, and c, together with the corresponding curves for excess static pressure Δp. Distinguishable on the oscillograms is the initial section showing the rapid rise of the pulse, and terminating at a maximum (Figures 1 a, b) or at a point of inflection (Figure 1 c). The time and pulse values corresponding to these points are designated T_* and I_*. The rate of change in the pulse decreased significantly thereafter. When the compression phase of the

explosion wave, T_+, ended, the magnitude of the pulse reached the value of I_+. It should be pointed out that the scatter in the results was greatly in excess of the measurement errors, particularly in the case of the magnitude of I_+. This can be explained, apparently, by the instability in the phenomenon investigated.

The magnitude of the time interval corresponding to the initial section can be represented in dimensionless form by $t_* = T_* c_1/D$, where c_1 is the speed of sound at the shock wave front. At the same time, in the cases investigated, the magnitude of t_* proved to be practically identical, and was, on the average, $t_* \approx 2.0$. Comparing this value with the results of the experiments made in connection with the investigation of the interaction of a cylinder with a plane shock wave [2], the conclusion is that the initial section of the rise in the pulse corresponds for the most part to the process of diffraction of the shock wave front at the cylinder. The magnitude of the dimensionless force pulse communicated to the body at moment t_* can also prove to be constant (within the limits of the scatter in the experimental data) /117

$$i_* = \frac{I_* c_1}{\Delta p_2 DS} \approx 0.7$$

Here Δp_2 is the excess pressure for normal reflection of the shock wave front, computed using the known values for p_o and Δp_1, and S is the area of the middle of the cylinder.

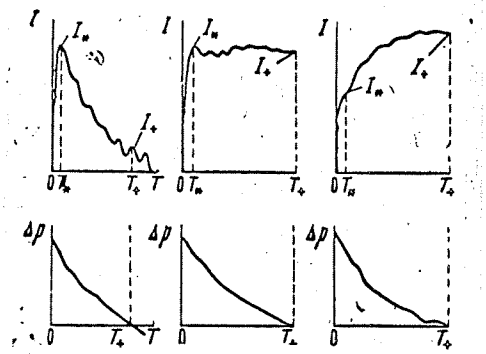

Figure 1.

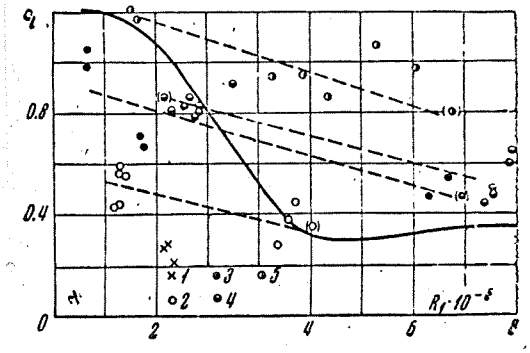

Figure 2.

The change in the pulse when $T_* < T < T_+$, is for the most part determined by the effect on the cylinder of the two forces acting in opposite directions, that is, by the velocity head of the unsteady incident gas flow, and by the force resulting from the presence of the negative pressure gradient and the velocity of the gas in the explosion wave. Consequently,

the magnitude I_+ can be less than, equal to, or greater than the magnitude I_* (Figure 1), depending on the flow regime.

It is of interest to compare the full pulse, I_+, communicated to the body at the moment the compression phase of the explosion wave terminates, with the pulse from the velocity head, I_o, for this same time interval. Their ratio, $I_+/I_o = c_i$, can be taken as the effective coefficient of resistance for the cylinder, averaged for time T_+. The basic parameters selected to characterize this coefficient can be the shock wave front Mach number, Reynolds number, and Strouhal number

$$M_1 = u_1/c_1, \qquad R_1 = \rho_1 u_1 D/\mu_1, \qquad S_1 = T_+ u_1/D$$

where u_1, ρ_1, μ_1 are velocity, density, and the viscosity factor for the gas at the front, computed using the relationships for a direct shock wave. The Mach number, M_1, was not in excess of 0.5 in the experiments conducted. As is known (from [5, 6], for example), in this range, and in the case of a steady flow over the cylinder, change in the Mach number has little effect on the dependence of the coefficient of resistance, c_x, on the Reynolds number (for $10^5 < R < 10^6$). Assuming this is also correct for the unsteady case, let us investigate the effect of just the Reynolds and Strouhal numbers on the coefficient c_i.

Figure 2 shows the values of the magnitude c_i obtained for this paper, and for purposes of comparison, the coefficient of resistance for a cylinder of infinite elongation in the case of a steady flow [5] (the solid curve) in terms of the Reynolds number. The pulse from the velocity head was established by using the results contained in reference [7].

All experiments were broken down into groups with similar Strouhal number values: 1 ($S_1 \approx 2.5$), 2 ($4.5 \leq S_1 \leq 6.5$), 3 ($7.5 \leq S_1 \leq 9.5$), 4 ($10.5 \leq S_1 \leq 14$), 5 ($21 \leq S_1 \leq 26$). Averaged curves for $c_i = c_i\ (R_1)$ were constructed for each group of points (with the exception of the group corresponding to the Strouhal number $S_1 \approx 2.5$). As will be seen from Figure 2, when R_1 = constant the effective coefficient of resistance for the cylinder will increase with increase in the Strouhal number. When the Strouhal number is constant c_i will decrease with increase in the Reynolds number, as in the case of the steady flow.

2. Formation of a nose wave by a flying body.

A spherical explosion wave was created using the same method as in paragraph 1. The body, accelerated to the necessary speed by a gas gun, was moved toward the wave front. The gun consisted of a barrel, a high-pressure chamber, and a quick-acting electrically operated valve installed between them.

A type IAB-451 schlieren interferometer visualized the interaction between the shock wave and the body. An SFR-2M streak camera (in the continuous scan mode) was used in combination with a generator providing flashes with a duration /118 of 0.1 microsecond and a spacing frequency of up to 30 kHz, to obtain the sequential series of images of the flow picture.

Taking the motion picture film of the interaction between the flying body and the explosion wave required selecting the moment the explosive charge was detonated, and the moment the gas gun's electrically operated valve was opened, so as to have the meeting between the body and the wave front take place in the field of view of the optical system and still have the mirror of the streak camera in a position such that the image would strike the motion picture film. This was accomplished by having the signal from the SFR-2M camera's synchro transmitter amplified and shaped and then fed into the unit controlling the electrically operated valve for the gas gun. This caused the valve to open and acceleration of the body to begin. This same signal passed through a delay line and triggered the unit that set off the explosive charge. The moment the shock wave neared the recording zone, the flash generator began to function, triggered by the piezoelectric synchronization pickup.

Figure 3 shows the schlieren photographs of the interaction between the spherical air explosion wave and a body flying toward its front. The body was a polystyrene foam cylinder with a hemispherical nose, 50 mm long, 20 mm in diameter, and weighing 0.7 gram. Speed of the body in nonturbulent air corresponded to a Mach number of $M = 0.82$. The excess static pressure at the wave front in the area of the encounter between the shock wave and the flying body was $1.2\ kg/cm^2$ for a compression phase of 3.5 milliseconds. All experiments were conducted at a normal atmospheric pressure of $1.03\ kg/cm^2$. The time intervals between the frames was 0.107 millisecond. The error in measuring the speed of the body was not in excess of 2%, that in the measurement of the excess static pressure 4%, and that in the measurement of the time interval 0.5%.

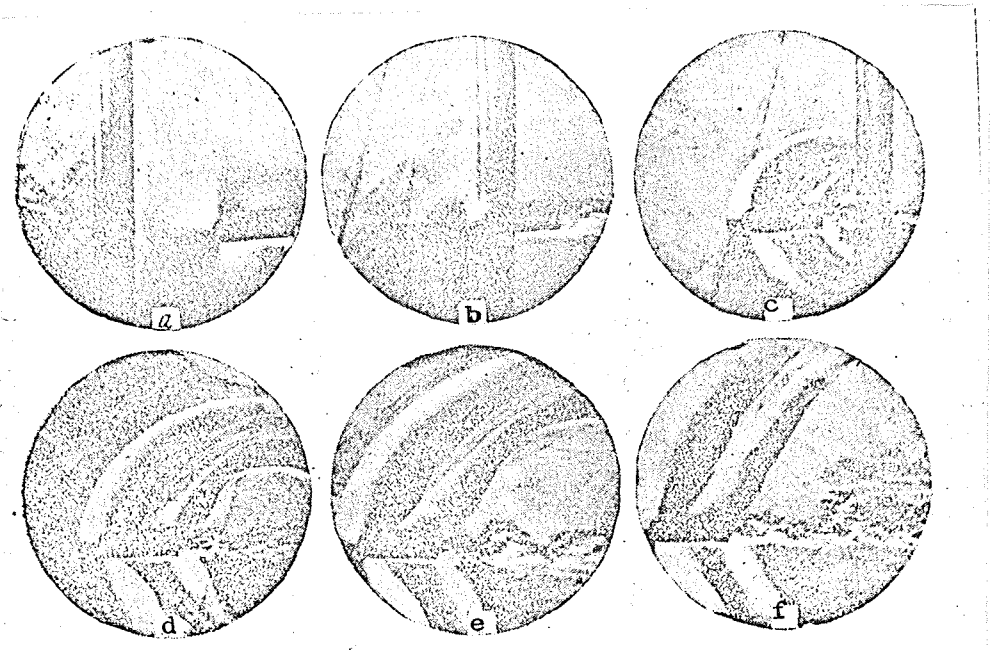

Figure 3.

The photographs show the intensive nose wave forming as the body enters the flow behind the explosion wave front. The domain delimited by the nose wave expands rapidly with time. At the same time, distance d from the leading critical point for the body to the nose shock wave also increases. Figure 4 shows the values of this distance in terms of the radius of bluntness of the nose, r, and of dimensionless time τ. In the figure $\varepsilon = d/r$, $\tau = {}^{1}/_{2}Tc_1/r$.

Here T is the time that has elapsed since the wave front and body met. Also seen is the relationship between ε and τ, obtained in experiments with a stationary sphere in a shock tube when the flows behind the shock wave were close to Mach numbers [8]. It can be pointed out that when $\tau \leq 2$ the ratio of ε to τ for a moving blunt cylinder and a stationary sphere are practically identical. With increase in τ the distance from the nose wave to the body in the shock tube becomes a fixed value corresponding to the shape of the body and the Mach number for the incident flow. The explosion wave can be characterized by a continuous drop in gas velocity with time, as a result of which the Mach number, M, for the flow incident to the body steadily decreases, and the nose wave recession increases accordingly. The dependence of the magnitude of ε on the local value /119 for M is the solid line in Figure 5. M magnitudes were computed using the materials contained in reference [7] with the experimental measurements of the

excess pressure values at the wave front and the speed of the body taken into consideration.

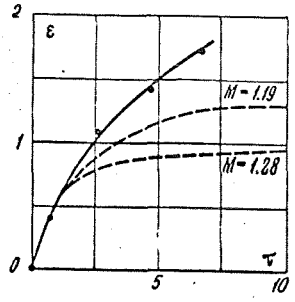

Figure 4.

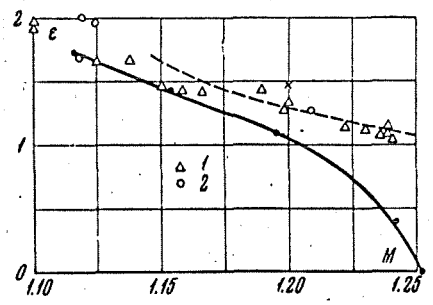

Figure 5.

This same figure shows analogous dependencies for the case of a steady flow over the sphere, obtained experimentally [8] 1, [9] 2, and computed through [10] (the dotted curve), as well as the value of the magnitude ϵ for $M = 1.2$, found by A. I. Golubinskiy for a body similar to that investigated in this paper (and designated by the x).

The experimental results shown in Figures 4 and 5 lead to the conclusion that the process involved in the formation of the nose wave in the case investigated can be broken down conditionally into two stages: the first, essentially unsteady; and the second, quasisteady. In the second stage, the distance between the nose wave and the body at each moment in time is close to the value obtained for a steady-state flow when the Mach number for the incident flow is changing. The transition from the first stage to the second begins at $\tau \approx 2$.

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